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Analysis of a photon number resolving detector based on an ion Coulomb crystal inside an optical cavity

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The ability to detect single photons with high efficiency is a crucial requirement for various quantum information applications. By combining the storage process of a quantum memory for photons with fluorescence-based quantum state measurement, it is in principle possible to achieve high efficiency photon counting in large ensembles of atoms. The large number of atoms can, however, pose significant problems in terms of noise stemming from imperfect initial state preparation and off-resonant fluorescence. We propose a concrete implementation of a photon number resolving detector based on an ion Coulomb crystal inside a moderately high-finesse optical cavity. The cavity enhancement leads to an effective optical depth of 15 for a finesse of 3000 with only about 1500 ions interacting with the light field. We show that these values allow for essentially noiseless detection with an efficiency larger than 90%. Moderate experimental parameters allow for repetition rates of about 5 kHz, limited by the time needed for fluorescence collection. Potential applications are discussed.

I. INTRODUCTION

Photons have repeatedly been proved to be excellent carriers of quantum information [1]. As such they play important roles in experiments that investigate the fundamental aspects of quantum mechanics, as well as in emerging quantum technologies. The final step in many of these scenarios is the detection of photons, making the detection efficiency a central parameter. Additionally, the number of photons in the experiments increases steadily, and as of today entangled states of as many as eight photons have been created [2]. Increasing the photon number even further will be extremely difficult without high-efficiency detectors. At the same time, some of the most fundamental experiments with not more than two photons have equally strong requirements. Loophole-free tests of Bell's inequalities, for example, can ascertain the non-local character of quantum mechanics, provided that the overall detection efficiency is greater than 82.8%[1] [3] . Still higher requirements are set by linear optics quantum computing based on realistic single-photon sources, where scalable entanglement-generating gates can only be achieved for a detection efficiency greater than 90% [4]. Additionally these gates need detectors that can distinguish a single-photon event from events with zero or multiple photons, i.e. a basic form of photon number resolution. The ability to distinguish different numbers of photons is an asset in many other situations. For example, it simplifies the implementation of device independent quantum key distribution, where the security of the key does not depend on the devices used for its generation [5]. It also opens up new opportunities in fundamental physics, such as the exploration of entanglement between microscopic and macroscopic objects [6].

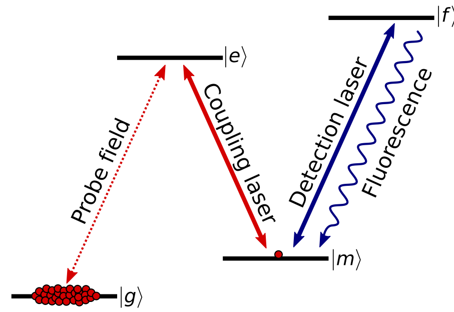

FIG. 1: Principle of the atom-based photon detector as originally proposed [7, 8]. First, an ensemble of identical atoms is prepared in their ground state $|g\rangle$. Next, photons in the probe field are converted into collective excitations in the metastable state $|m\rangle$ with the help of a coupling laser. Finally, the number of collective excitations is probed by collecting fluorescence on the closed transition $|m\rangle \leftrightarrow |f\rangle$

The high demands set by quantum optics applications have in recent years led to significant developments in single-photon detection technologies. State-of-the-art silicon-based avalanche photo diodes have peak efficiencies of around 70% and low dark count rates, but currently the ability to distinguish photon numbers remains limited [11]. Detectors that reach efficiencies above 90% while at the same time maintaining a low dark count rate are still scarce [12]. Only recently, close to unit efficiency and negligible dark counts have been demonstrated with transition edge sensors [13]. While these devices also show photon number resolution for small photon numbers, their low operating temperature of 100 mK requires

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[1] It is possible to relax the requirement on the detection efficiency down to $\eta = 2/3$ by using non-maximally entangled states [3]. However, this requires extreme signal-to-noise ratios.

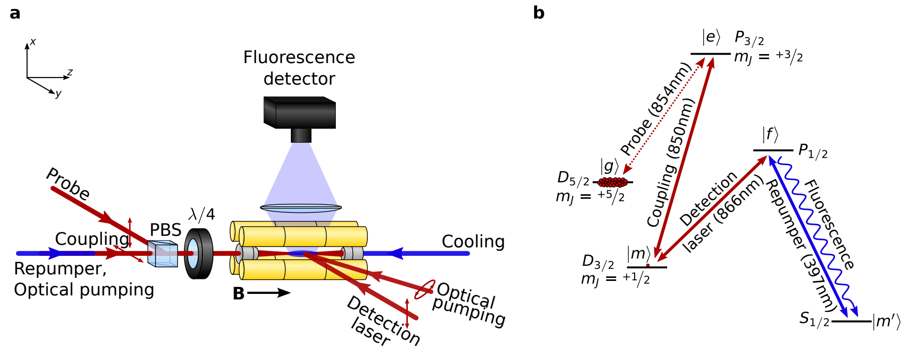

FIG. 2: Implementation of the photon detector based on a Coulomb crystal of $^{40}\mathrm{Ca}^+$ ions inside an optical cavity. (a) The laser beams for cooling, optical pumping, as well as the probe and coupling fields travel along the cavity axis in order to avoid Doppler shifts due to rf induced micromotion [9, 10]. Additional laser beams are used for a second optical pumping step and exciting fluorescence. The fluorescence is collected with a large numerical aperture lens and directed towards a detector. (b) Diagram that shows which energy levels of $^{40}\mathrm{Ca}^+$ take the roles specified in Fig. 1.

sophisticated cooling technology.

We present a feasibility study of a high efficiency photon number resolving detector based on a Coulomb crystal of $^{40}\mathrm{Ca}^+$ ions placed inside an optical cavity. Our scheme is a concretization of previous proposals suggesting the use of an ensemble of atoms to convert a single photon into many fluorescence photons, which are then readily detected [7, 8]. We will show that high efficiency can be reached with a relatively small number of ions and a moderate finesse cavity, making faithful photon counting feasible. Furthermore, the reduced number of atoms compared to the original proposals alleviates some technical issues.

The gist of the original proposals [7, 8] is illustrated by means of the energy level diagram in Fig. 1. They suggest to combine two key technologies. First, photons in a probe pulse are coherently converted into collective excitations in an atomic ensemble using light storage based on electromagnetically induced transparency (EIT) [14]. Then the number of collective excitations is probed by measuring resonance fluorescence as usually employed in ion trap experiments [15]. The whole procedure works as follows. An ensemble of atoms is initially prepared in a specific ground state $|g\rangle$. The light field to be measured is resonant with the transition $|g\rangle \leftrightarrow |e\rangle$. It takes the role of the probe field in an EIT scheme, and is coherently mapped onto a collective excitation in the metastable state $|m\rangle$ by applying a strong coupling laser on the transition $|m\rangle \leftrightarrow |e\rangle$. Finally, a detection laser couples $|m\rangle$ to a fourth state $|f\rangle$, which spontaneously decays back to $|m\rangle$ only. The scheme inherently exhibits photon number resolution since the amount of fluorescence emitted on the transition $|m\rangle \leftrightarrow |f\rangle$ is directly proportional to the number of photons in the probe field.

The conversion of the photons in the probe field to collective excitations in the atomic ensemble can in principle be made arbitrarily efficient by increasing the number of atoms in the ensemble. For a cold gas the required number of atoms is on the order of $N = 10^6$. Such a large number of atoms leads to a series of technical problems. The first problem arises during the initialization of the atoms. Since any atom in $|m\rangle$ will contribute to the fluorescence at the detection stage, this state has to be emptied completely, requiring optical pumping with extremely high efficiency. For alkali atoms, considered in the original proposals, the states $|g\rangle$ and $|m\rangle$ would typically belong to the two hyperfine manifolds of the $S_{1/2}$ ground state, separated in energy by a hyperfine splitting Δ_{HFS} on the order of a few gigahertz. The state $|f\rangle$ is part of the $P_{3/2}$ manifold with a line width $\Gamma \approx 10$ MHz. The probability of unwanted off-resonant excitation of an atom from $|g\rangle$ during the detection stage is on the order of $\Gamma^2/\Delta^2_{\mathrm{HFS}} \approx 10^{-6}$. For one million atoms this noise is comparable to the signal from a few-photon probe field. Finally, the collection of a sufficient amount of fluorescence can be impeded by a premature loss of the atoms from the trap caused by heating and light-assisted collisions [16].

A concrete system which significantly reduces or avoids the problems mentioned above is shown in Fig. 2. It consists of an ion Coulomb crystal [17, 18] with $N \approx 1500$ Ca^+ ions interacting with the field of an optical cavity with a moderately high finesse of $\mathcal{F} \approx 3000$. In the ions, the metastable states $D_{5/2}$ and $D_{3/2}$ (lifetimes ~ 1.15 s) take the roles of $|g\rangle$ and $|m\rangle$, respectively, while $P_{3/2}$ is $|e\rangle$ and $P_{1/2}$ is $|f\rangle$. Since ions in the $P_{1/2}$ ($|f\rangle$) state can spontaneously decay to $S_{1/2}$ ($|m'\rangle$), a repumper is needed to address the $|f\rangle \leftrightarrow |m'\rangle$ transition. The fluorescence rate on this transition is in fact more than ten times higher than on the $|f\rangle \leftrightarrow |m\rangle$ transition, and hence most optimal for the final fluorescence detection.

Essential ingredients of the proposed photon detector have already been applied in recent experiments demonstrating strong collective coupling [19] and cavity EIT [20]. While the experiments reported in Refs. 19, 20 were carried out between sub-states of the $D_{3/2}$ level, previously, very efficient ($> 90\%$) coherent STIRAP population transfer between $D_{3/2}$ and $D_{5/2}$ states had been

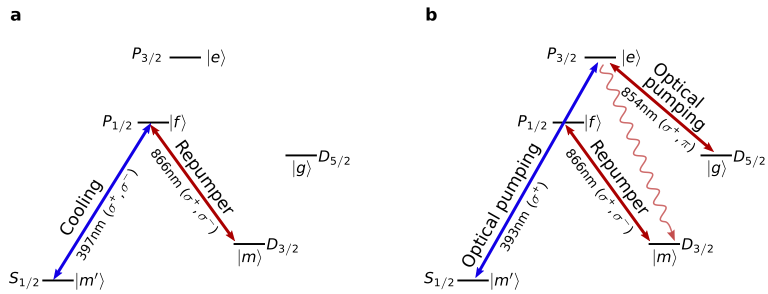

FIG. 3: Energy levels and relevant transitions for the initialization of the photon detector in $^{40}\mathrm{Ca}^+$. (a) The ions are laser cooled by driving the $S_{1/2} \leftrightarrow P_{1/2}$ transition at 397 nm and repumping on the $D_{3/2} \leftrightarrow P_{1/2}$ transition at 866 nm. (b) Optical pumping to the $m_J = +5/2$ Zeeman substate of the $D_{5/2}$ level is accomplished by two optical pumping beams on the $S_{1/2} \leftrightarrow P_{3/2}$ (393 nm) and $D_{5/2} \leftrightarrow P_{3/2}$ (854 nm) transitions. The repumper takes care of atoms that spontaneously decay from $P_{3/2}$ to $D_{3/2}$.

realized [21].

II. PROTOCOL

In the following the individual steps of the photon detection protocol will be discussed in detail. Every step of the protocol determines one of the characteristics of the detector: the successful initialization significantly reduces the probability of dark counts, the probability of successful light storage equals the overall efficiency of the detector, and the time required for fluorescence collection limits the repetition rate of the detector.

A. Initialization

The goal of the initialization is the preparation of a cold Coulomb crystal with the ions in state $|g\rangle = |D_{5/2}, m_J = +5/2\rangle$. The preparation consists of several steps similar to the preparation described in Ref. 19. A magnetic field of a few Gauss along the cavity axis defines the quantization axis, and laser cooling is achieved by applying two counter-propagating light beams along the cavity axis. The light is resonant with the $S_{1/2} \leftrightarrow P_{1/2}$ transition at 397 nm, and the beams are left and right-hand circularly polarized, respectively (see Fig. 3). Atoms that fall into the $D_{3/2}$ state are repumped by a laser at 866 nm applied from the side with its polarization orthogonal to the cavity axis, equivalent to left- and right-hand circularly polarized with respect to the quantization axis. Once the ions are sufficiently cold, the cooling laser is turned off. Two additional lasers pump the ions to the $m_J = +5/2$ Zeeman sublevel of the $D_{5/2}$ state. The first of these lasers drives the σ^+-transitions from $S_{1/2}$ to $P_{3/2}$. The second laser is resonant with the $D_{5/2} \leftrightarrow P_{3/2}$ transition, and its propagation direction and polarization are chosen such that σ^+ and π transitions are addressed simultaneously. Atoms that spontaneously decay from $P_{3/2}$ to $D_{3/2}$ are reintroduced into the optical pumping process by the laser cooling repumper. A typical duration of the cooling and pumping procedure is 25 μs [22].

Efficient optical pumping is very important for high fidelity measurements of the photon number in the probe field. Ions that are not in state $|g\rangle$ after the initialization may offset the fluorescence in the final step of the detector protocol, leading to an overestimation of the photon number. Ref. 19 states an optical pumping efficiency to the $D_{3/2}$ level with $m_J = +3/2$ of 97%. Optical pumping into the $m_J = +5/2$ sub-state of the $D_{5/2}$ state is expected to have a similar efficiency. The remaining ions will mainly be distributed over the other $D_{5/2}$ sub-states, because the pumping and repumping fields dominate the rather weak spontaneous decay rate into $D_{3/2}$ of only $2\pi \times 0.18$ MHz. Ions ending up in $S_{1/2}$ or $D_{3/2}$ will, however, contribute to the detector dark counts. More precisely, for N_{SD} ions in these states, a probability of absorption of the incoming photon of η, and n photons in the probe field, the signal-to-noise ratio is $\eta\, n/N_{SD}$. However, N_{SD} can be estimated by monitoring the ultraviolet fluorescence during the optical pumping, and the result subtracted from the photon number measurement. Alternatively, one can extend the dead time of the detector by a variable amount and let optical pumping proceed until the moment when the monitored fluorescence ceases. This signals that the relevant energy levels are empty, and the detector is ready to receive the probe pulse. We note that the larger the total number of ions, the more difficult it is to keep N_{SD} negligible.

B. Light storage

In the second step of the detector protocol, the photons in the probe pulse are converted into collective excitations in the metastable state $|m\rangle$. The procedure is the same as the absorption of photons into a quantum memory for light, based on an ensemble placed inside an optical cavity [23]. The most essential parameter of such

memories is the cooperativity[2] $C = g^2N/\kappa\gamma^2$, where $g\sqrt{N}$ is the collective coupling rate between the ensemble and a cavity photon, κ is the cavity decay rate and $1/\gamma$ is the lifetime of the excited state $|e\rangle$ in the protocol. The cooperativity both determines the maximally obtainable photon conversion efficiency $\eta = C/(1+C)$ as well as sets a bound on the temporal length T of the photonic probe pulse via $T \gg 1/C\gamma$ [24, 25].

The efficiency of the light storage determines the overall detection efficiency, as long as saturation effects are avoided by ensuring that the number of photons in the probe pulse is much smaller than the number of ions. Considering previous parameters experimentally realized [19], a cooperativity of $C = 15$ or more should be feasible, which gives a detection efficiency above 93%.

To avoid unwanted Doppler efffects related to rf induced micromotion (see references in the caption to Fig. 2), the coupling field has to co-propagate with the probe field inside the cavity, as indicated in Fig. 2. In this case the geometrical constraints on the spatial profile of the coupling field reduce the optimal storage efficiency by an amount that depends on the radial extension of the Coulomb crystal. However, this reduction can be rendered negligible by carefully choosing the size of the crystal, adjusting the strength of the coupling field, or constraining the radius by addition of a second calcium isotope [25].

C. Fluorescence collection

In the last step of the protocol, the number of ions transferred to the $D_{3/2}$ state is measured by fluorescence collection. Fluorescence collection is routinely applied in trapped-ion based quantum computing, and a single-ion state-discrimination with an error probability below 10^{-4} has been reported [26]. The fluorescence is induced by the same lasers that were used during the cooling stage (Fig. 3a). Ions in one of the the $D_{3/2}$ will emit fluorescence on the $S_{1/2} \leftrightarrow P_{1/2}$ transition. The amount of fluorescence is proportional to the number of ions undergoing the optical cycling. For unit absorption efficiency and an ideal initialization of the detector, this number is equal to the number of photons originally present in the probe pulse. Since the detection laser is 12 nm detuned from the $D_{5/2} \leftrightarrow P_{3/2}$ transition, the ions that remained in $D_{5/2}$ are not affected at all.

We shall now try to estimate the rate of detected fluorescence photons per ion. Assuming that all the involved optical transitions are satured, every ion spends about 1/4 of its time in $P_{1/2}$, from where it spontaneously decays into $S_{1/2}$ at a rate of $\gamma_{PS} = 2\pi \times 20.7$ MHz. Letting Θ denote the amount of solid angle covered by the collection system, and η_D the overall detection efficiency at the relevant wavelength of 397 nm, the photon detection rate per ion is given by $R = \gamma_{PS}\Theta\eta_D/16\pi$. Assuming that a measurement becomes conclusive for 30 detected photons per ion, and that typical (moderate) experimental parameters are $\Theta/4\pi = 0.02$ and $\eta_D = 0.4$, fluorescence needs to be collected for about $t = 120$ μs. Although the lifetime of the D-states is $\tau_D = 1.15$ s $\gg t$, it can happen that an atom decays from $D_{5/2}$ to $S_{1/2}$ during the fluorescence collection. For $N = 1500$ ions, the average number of decays is given by $N_{\mathrm{decay}} = N(1 - \exp -t/\tau_D) = 0.16$, thus only leading to a minor correction of the signal-to-noise ratio.

After the fluorescence detection, the ions will have to undergo a brief period of laser cooling before reinitialization back into $D_{5/2}$. Based on previous experiments [19, 20], this procedure is expected to take less than 100 μs.

III. CONCLUSION

In summary, we have presented a concrete implementation of an atomic-ensemble-based photon number resolving detector based on a Coulomb crystal of $^{40}\mathrm{Ca}^+$ ions inside an optical cavity. For a currently available system, a detection efficiency of $\eta \approx 93\%$ is already feasible. The efficiency can be improved by increasing the cooperativity, e.g. by applying a cavity with a higher finesse, a larger Coulomb crystal, and/or spatially controlling the ions positions with respect to the anti-nodes of the standing-wave light field [27, 28]. A detection efficiency of better than 98% is thus within reach. Different photon numbers can be distinguished as long as the number of photons is much lower than the number of ions. For 1500 ions, photon number resolution can probably be maintained up to a few tens of photons. However, for more than ~ 10 input photons the non-unit detection efficiency and the Poissonian counting statistics of fluorescence will limit the achievable fidelity. Furthermore, it should be possible to reduce the dark counts to a negligible level, provided that the quality of the initialization can be assured and the fluorescence collection time kept short. On the downside, the detector can be considered as rather slow in terms of repetition rate and bandwidth. Currently, the repetition rate would be limited to about 5 kHz, caused by the rather long fluorescence detection. Improvements of the experimental setup could probably push this to about one measurement every 50 μs. This would correspond to the time it takes for a signal to travel through 10 km of optical fibre, and should hence be sufficient for, e.g., the next generation of long-distance quantum communication experiments [29]. The bandwidth of the photons in the probe pulse is limited by the adiabaticity condition $T \gg 1/C\gamma$ for the light storage. For our proposed implementation using ^{40}Ca this translates into a bandwidth significantly smaller than $C\gamma/2\pi \approx 90$ MHz.

[2] We will use the definition of the cooperativity as given in ref. 24. Please note that definitions given in other references may differ by a factor of 2.

The improvements of the cooperativity discussed above can probably gain a factor of 4 to 5. However, many tasks in optical quantum information processing also necessitate quantum memories, whose bandwidth is equally limited. In fact, the kind of photon detector presented here is a quantum memory without retrieval, and it is imaginable that other kind of quantum memories can be used in a similar way, extending the range of applications for quantum memories considerably.

Acknowledgments

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